Narrow-Angle Astrometry

Michelson Summer School

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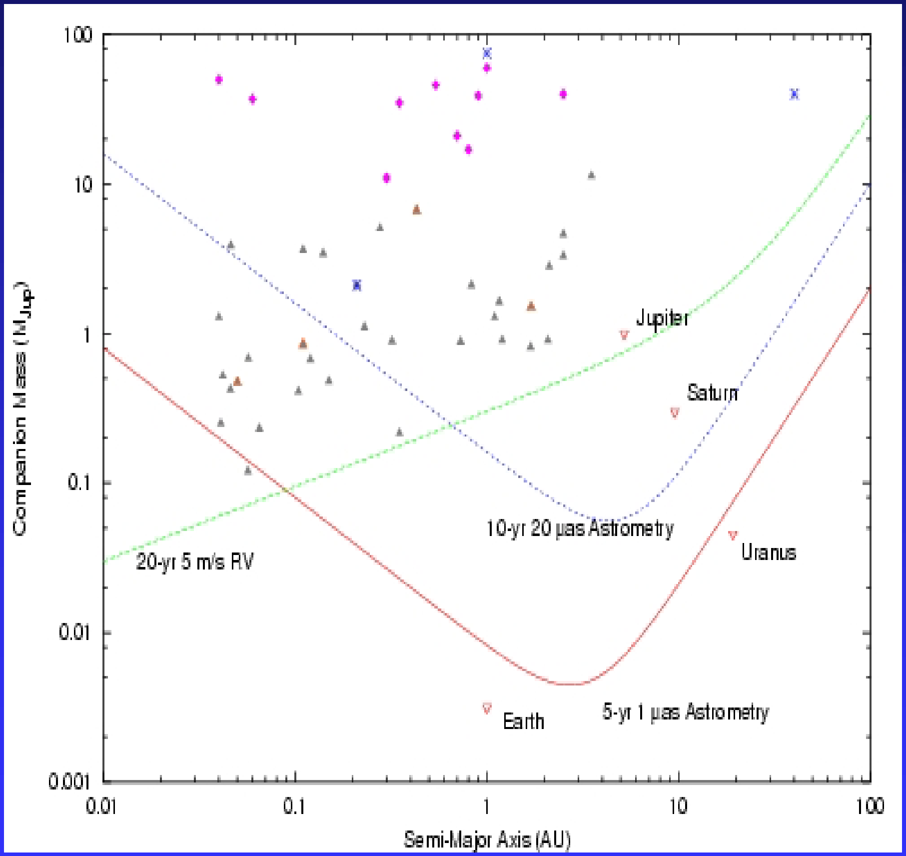
Overview

- Motivation
- Theory
- Sources of Error
- Example
- Phase Referencing
- Future Design Considerations

Astrometry & Planets

$$\Delta\theta \cong 1000 \frac{m_p / m_J}{M_* / M_S} \frac{a/\mathrm{AU}}{D/pc}\ \mu\mathrm{asec}$$

- Good comlement to RV, especially for outer planets.
- Astrometry provides inclinations, masses



Gravitational Microlensing

- Astrometry + Photometry of lensing events allows one to determine lens mass and distance.
- Need high precision (10 micro-arcsec).
- Lens events often very faint (K~16).

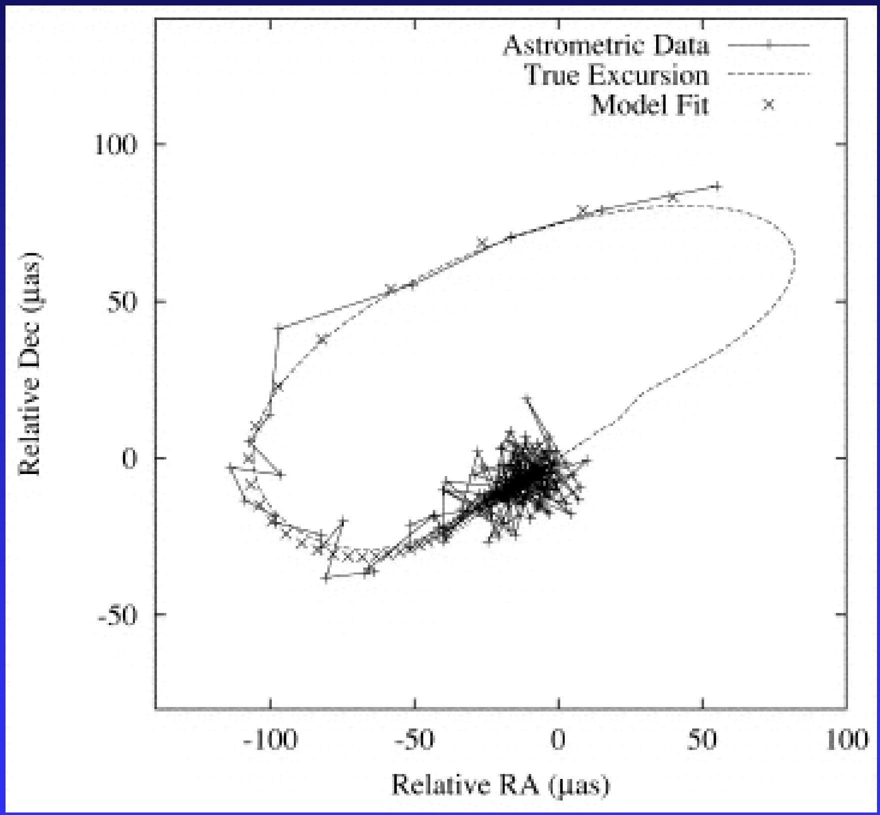


Figure from Boden, Shao & van Buren, 1998

Top-Level Requirements

- ~20 micro-asec over 10 years
- For planet studies: m_K ~10 for target, ~14 for references (to get few hundred targets).
- For micro-lensing: m_K ~16 for target, likely need nearby bright reference.
  - Possible to have a few brighter ones (m~10), need to know proper motions.

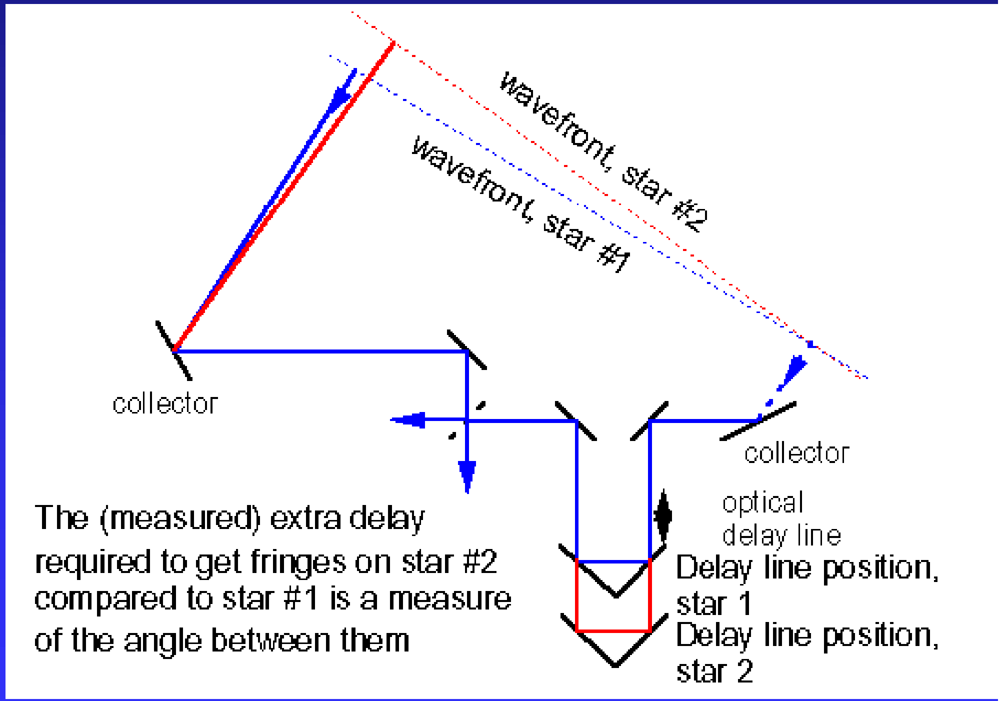
Interferometric Astrometry

- Delay equation:

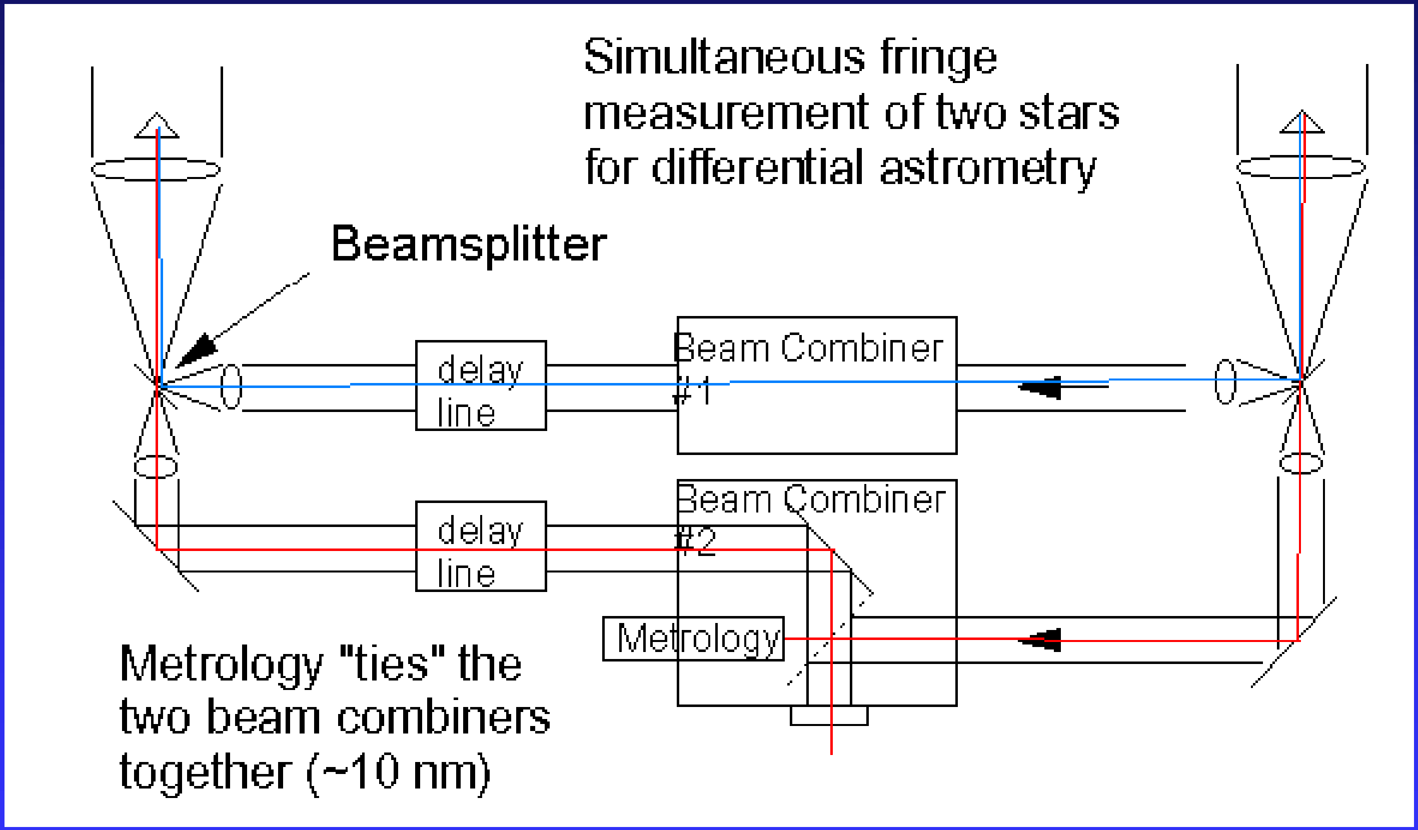
$$d = \vec{B} \bullet \vec{s} + c$$

$$\Delta d = \vec{B} \bullet \Delta\vec{s}$$

For 100-m baseline & 5 nm delay precision, we can expect 10 micro-arcsecond precision.



Dual-Star Interferometry



Noise Sources

- 10 Micro-arcsec is great! But:
  - Atmospheric Noise
  - Baseline Knowledge Errors
  - Instrumental Path Errors
  - Detector Noise

$$\sigma_s \approx rss[\frac{\delta d}{|B|}, k^{-1}\frac{\delta\phi}{|B|}, \frac{\delta B}{|B|}\Delta s]$$

Atmospheric Noise (1 of 3)

- Turbulent atmosphere induces fringe motion (seeing):
  - ~10 ms, 10 cm at 0.5 microns.
  - Recall: $r_0 \propto \lambda^{6/5}$
- Less severe for near-IR
  - Note that "coherence volume" $\propto \lambda^{18/5}$
  - K band (2.2 microns) seems to be optimal choice.

Atmospheric Noise (2 of 3)

- Over narrow fields (~30-60 arcsec) atmospheric error is correlated and can largely be subtracted out.
- Most sensitive to high-altitude turbulence
  - From: $$\sigma_d^2 \propto \frac{1}{t}\int dh C_n^2(h) h^2$$
- Need to consider unusual instrument sites, i.e. South Pole (no jet stream).

Atmospheric Noise (3 of 3)

- Short Baseline:

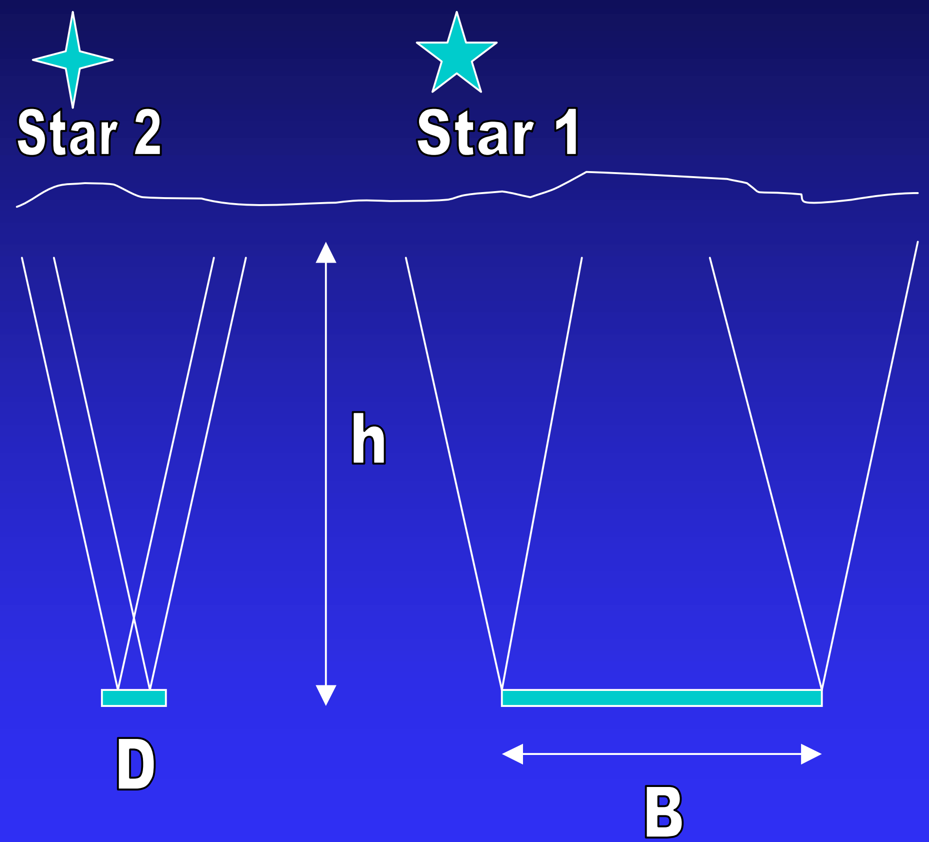
  $\theta h >> D$

  $\sigma_d \propto \theta^{1/3}$

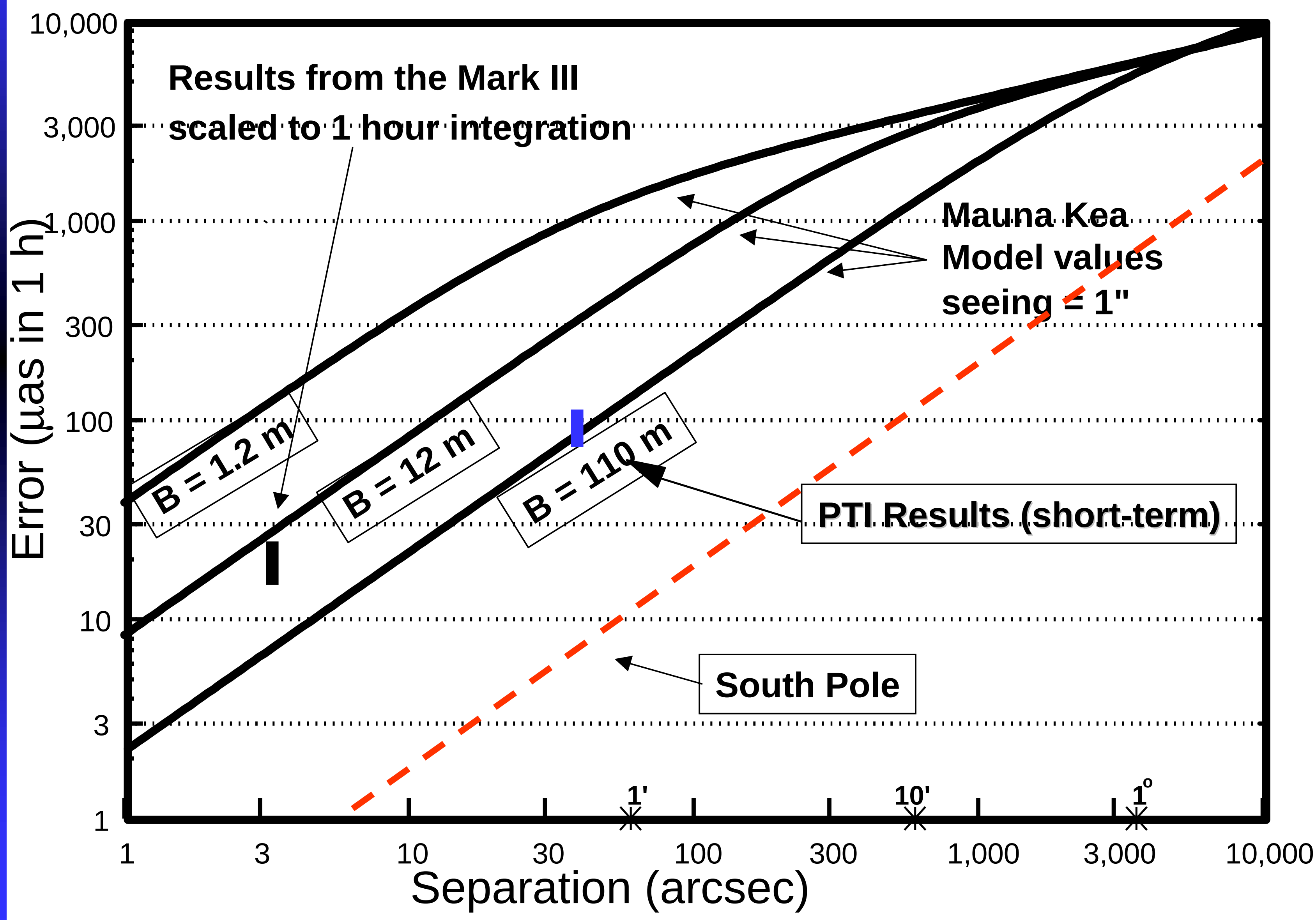
- Long Baseline:

  $\theta h << B$

  $\sigma_d \propto \theta B^{-2/3}$

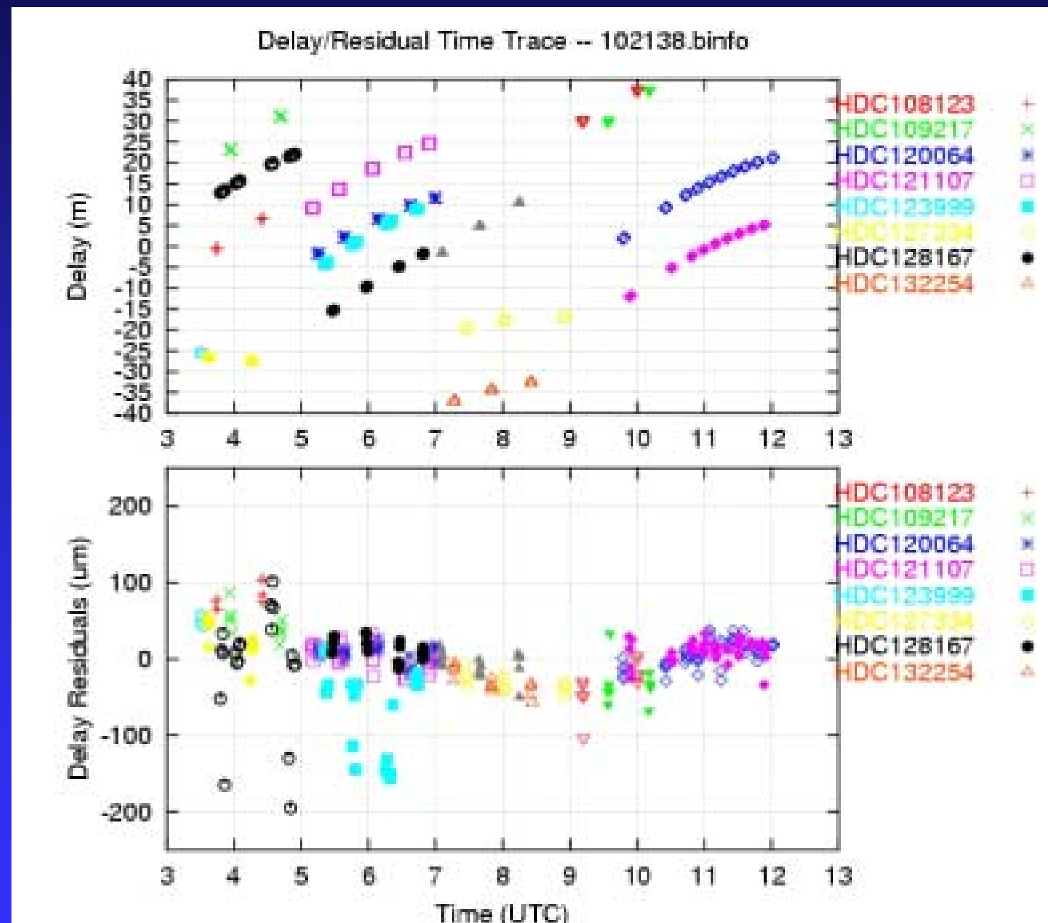


Atmospheric limits to a narrow-angle measurement



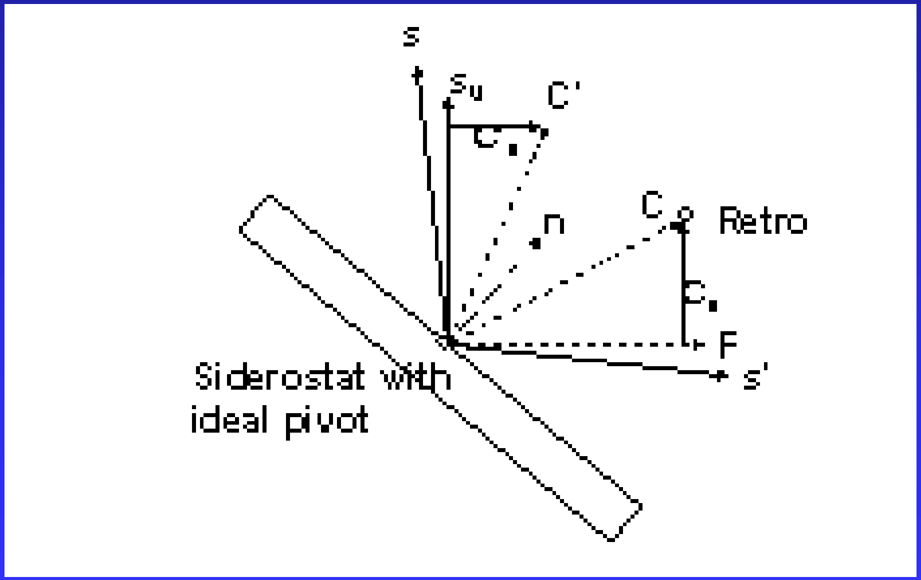
Wide-Angle Baseline

- Need to know baseline to ~50 microns.
- Measure fringe position of many known stars, solve $d = \vec{B} \bullet \vec{s} + c$
- Need milli-arcsecond level astrometry.



Instrumental Path Errors

- Internal laser metrology fiducial is not located at pivot points that define the wide-angle baseline.
- Gives error term that looks like a correction to the baseline.
- Need to know CC location to high accuracy (~50 μm).



Detector Noise (1 of 2)

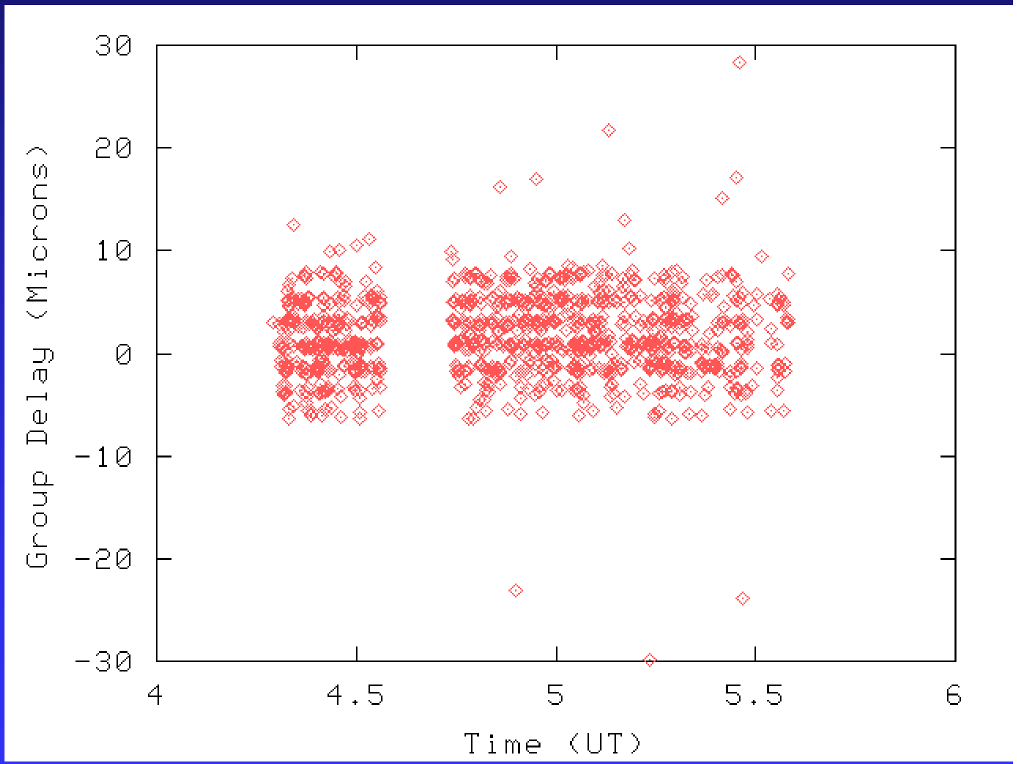
- The fringe tracker measures the fringe phase with limited precision

$$\delta\phi \approx \frac{1}{SNR} \qquad \text{where} \qquad SNR^2 = \frac{(NV)^2}{2\left(N + B + 4\sigma^2\right)}$$

- Need enough photons to get non-zero SNR in a coherence volume

Detector Noise (2 of 2)

- A phase-tracking interferometer can track the wrong fringe in envelope.
- Hence requires group delay tracking:
  - Use spectral dispersion to measure phase vs. wavelength.

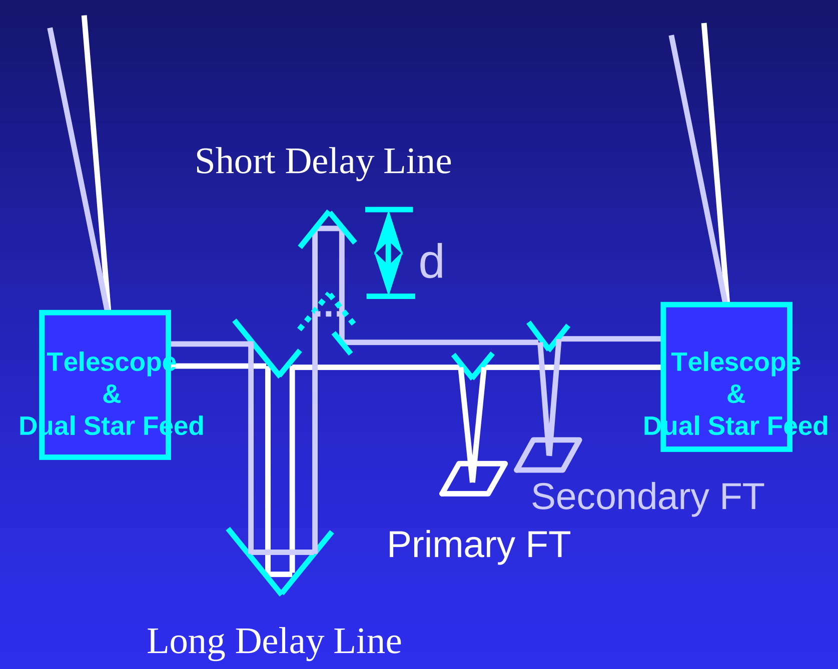


Noise Summary

- Atmosphere imposes ~10-100 micro-arcsec depending on atmospheric details – pick good site.
- Wide-angle baseline knowldege required to ~50 microns – known technology.
- Instrumental path errors must be controlled – instrument design critical.
- Longer baselines help.

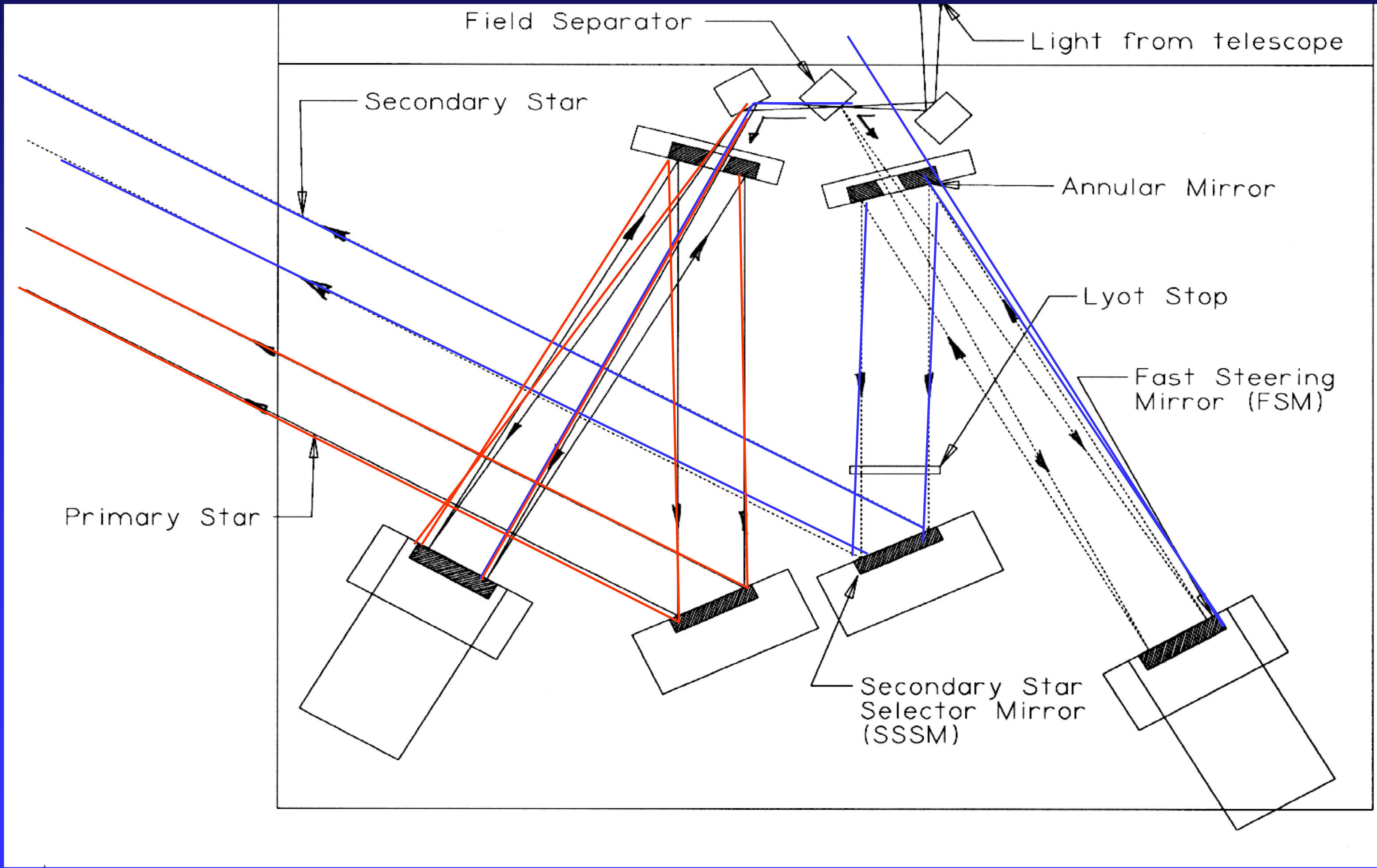
Narrow-angle astrometry with PTI

- Dual-star feed to separate out target star from astrometric reference
- Dual beam combiners to allow simultaneous measurements
  - One beam combiner tracks target star
  - Second beam combiner switches between target & reference
- Laser metrology to measure internal delay

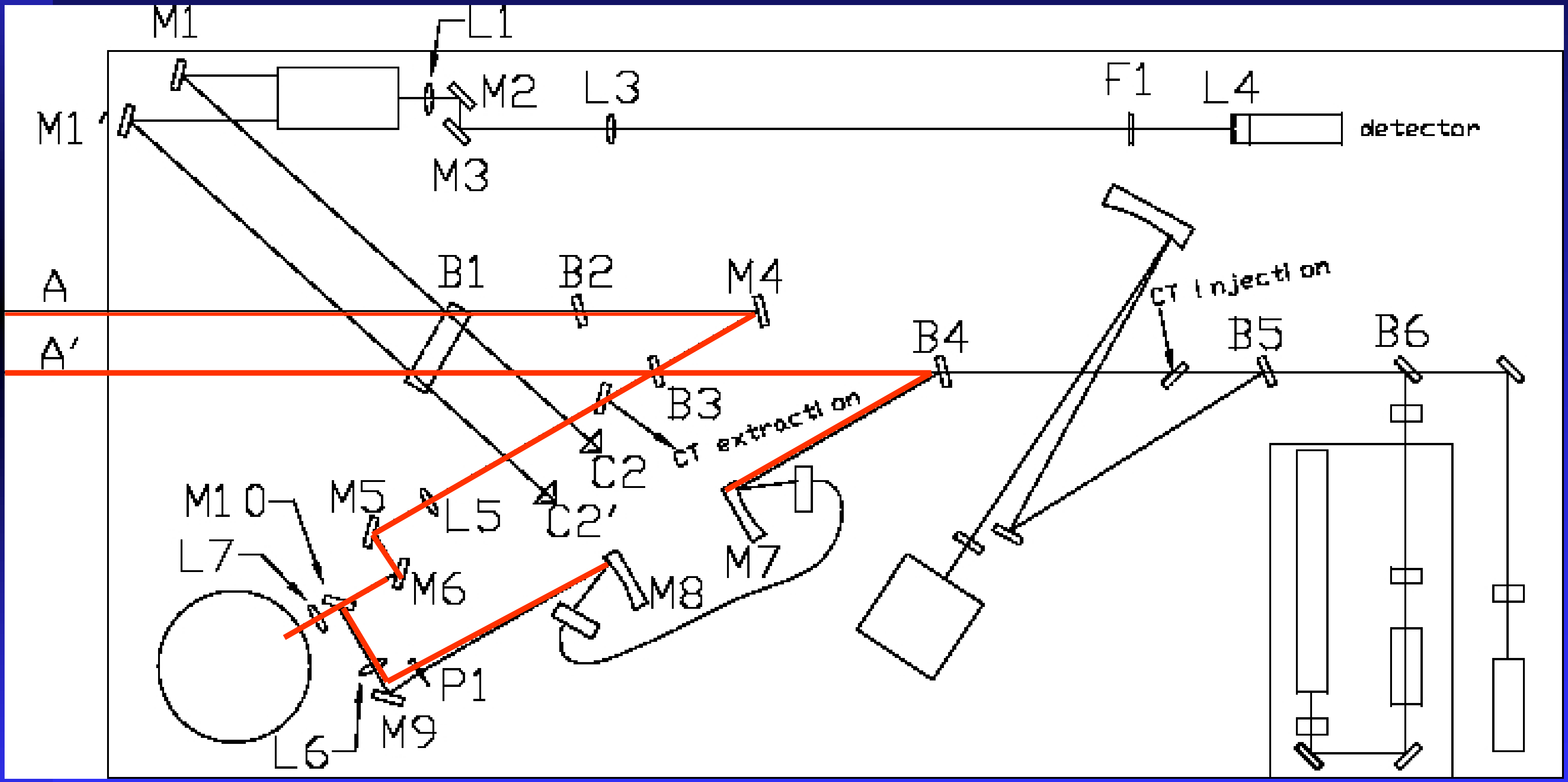


Siderostat

Dual-star module



Beam Combiner



61 Cyg Astrometry (1 of 5)

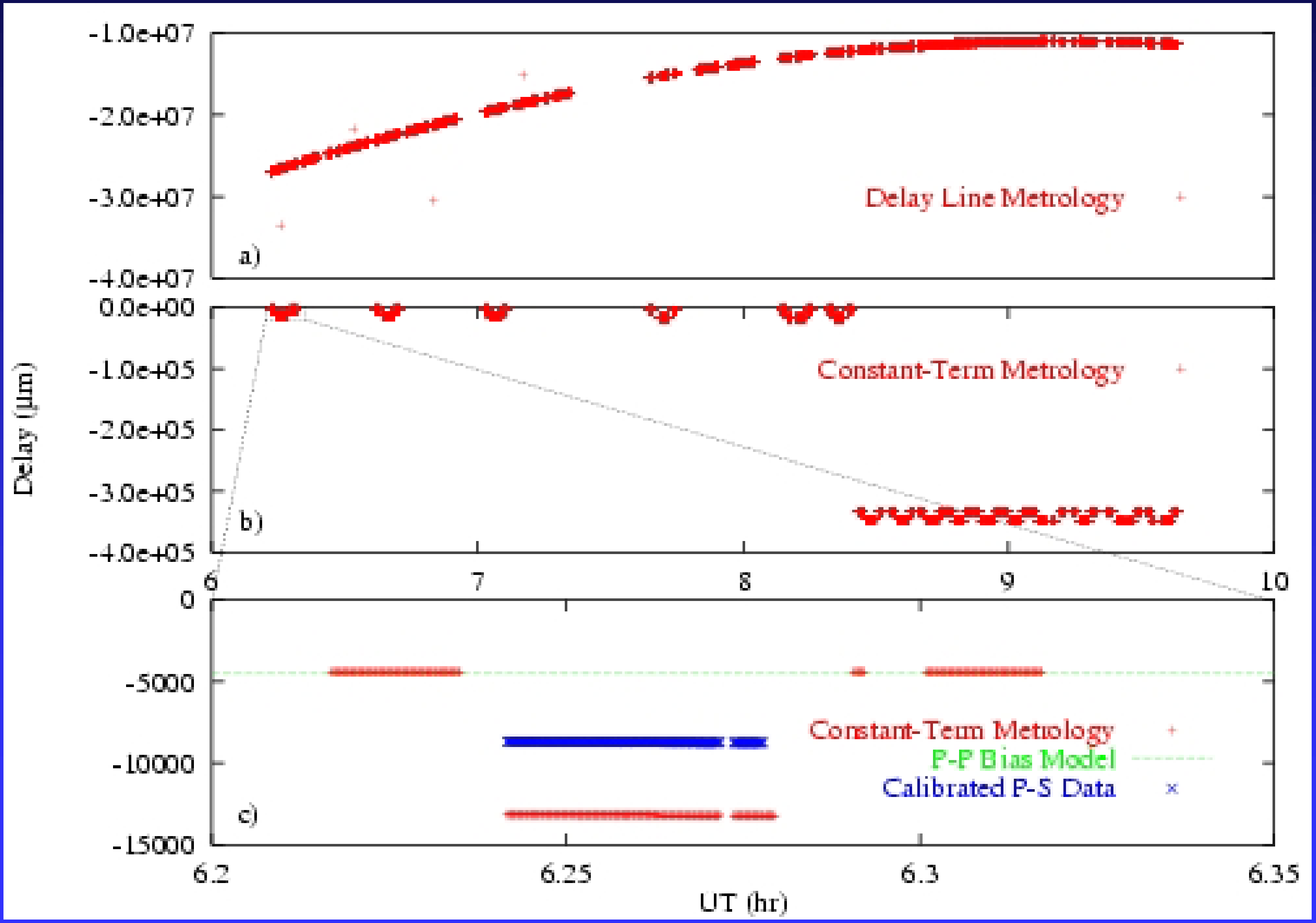


Figure by A. F. Boden & ISC

61 Cyg Astrometry (2 of 5)

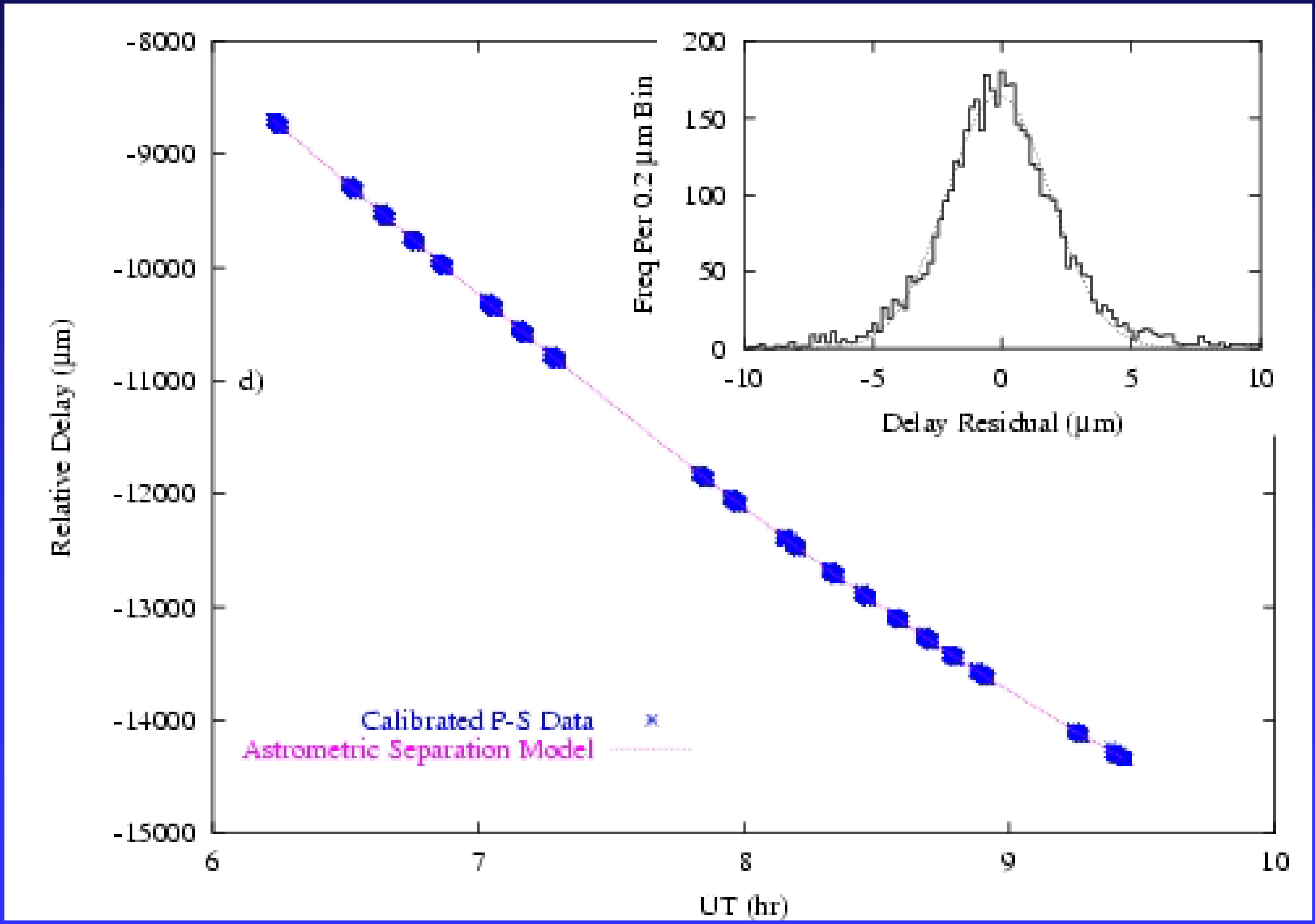
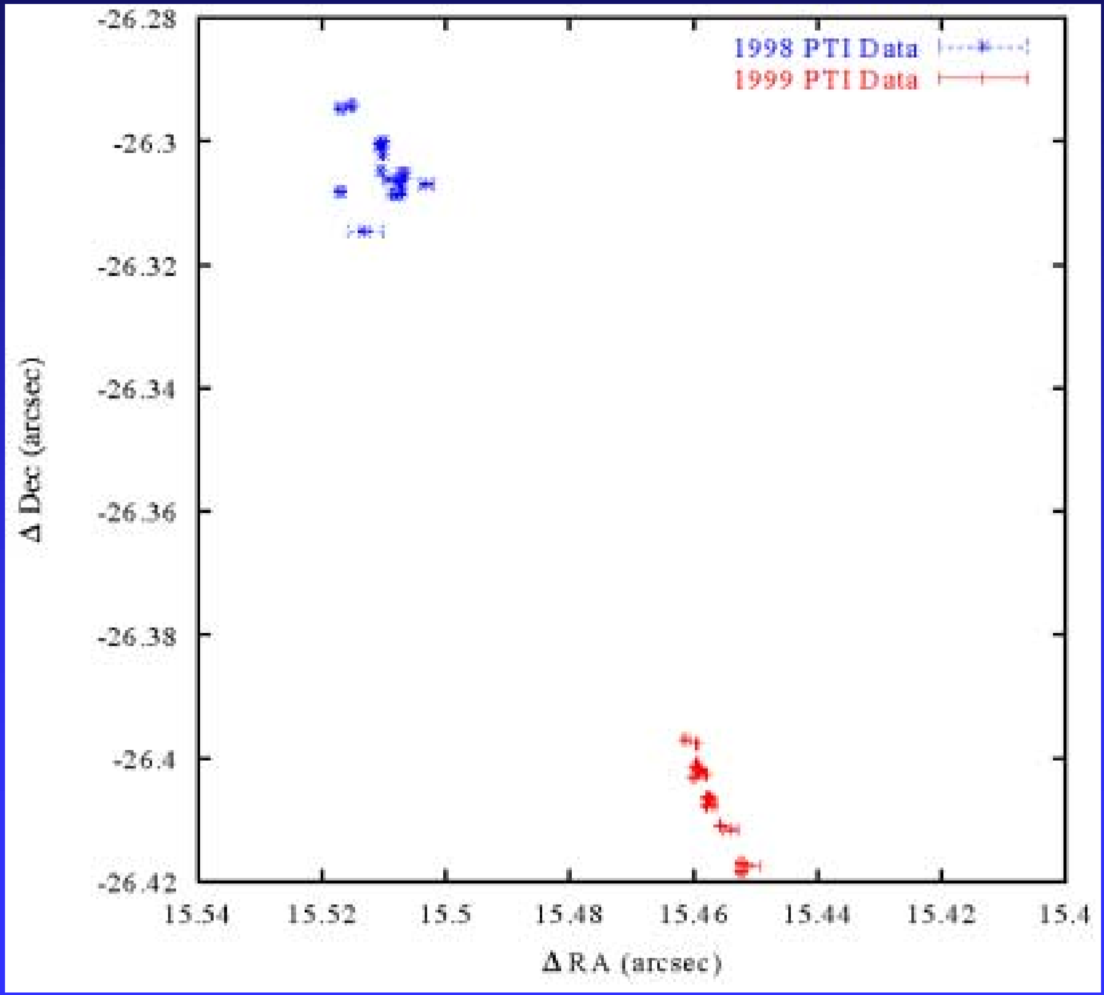
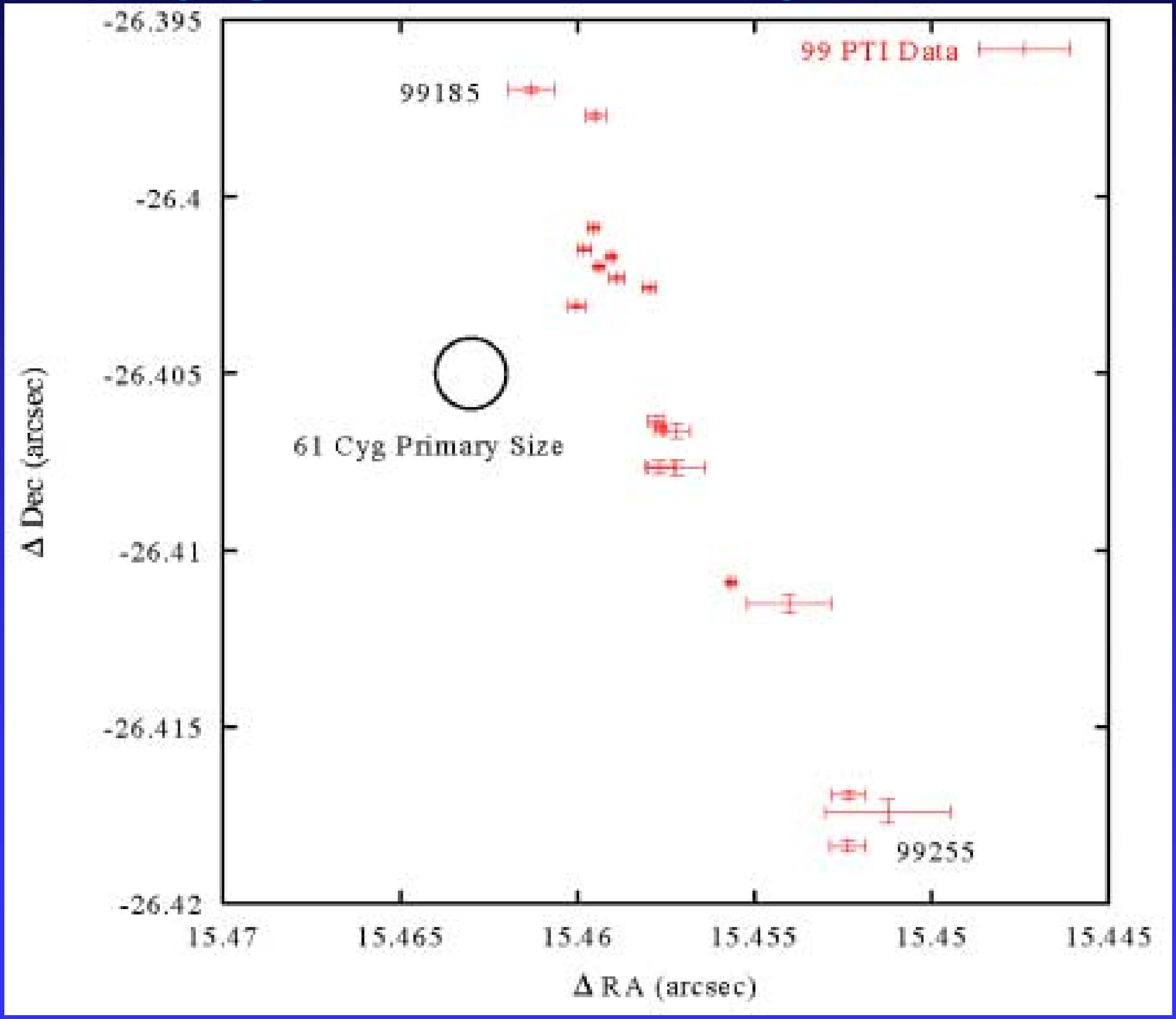


Figure by A. F. Boden & ISC

61 Cyg Astrometry (3 of 5)



61 Cyg Astrometry (4 of 5)



61 Cyg Astrometry (5 of 5)

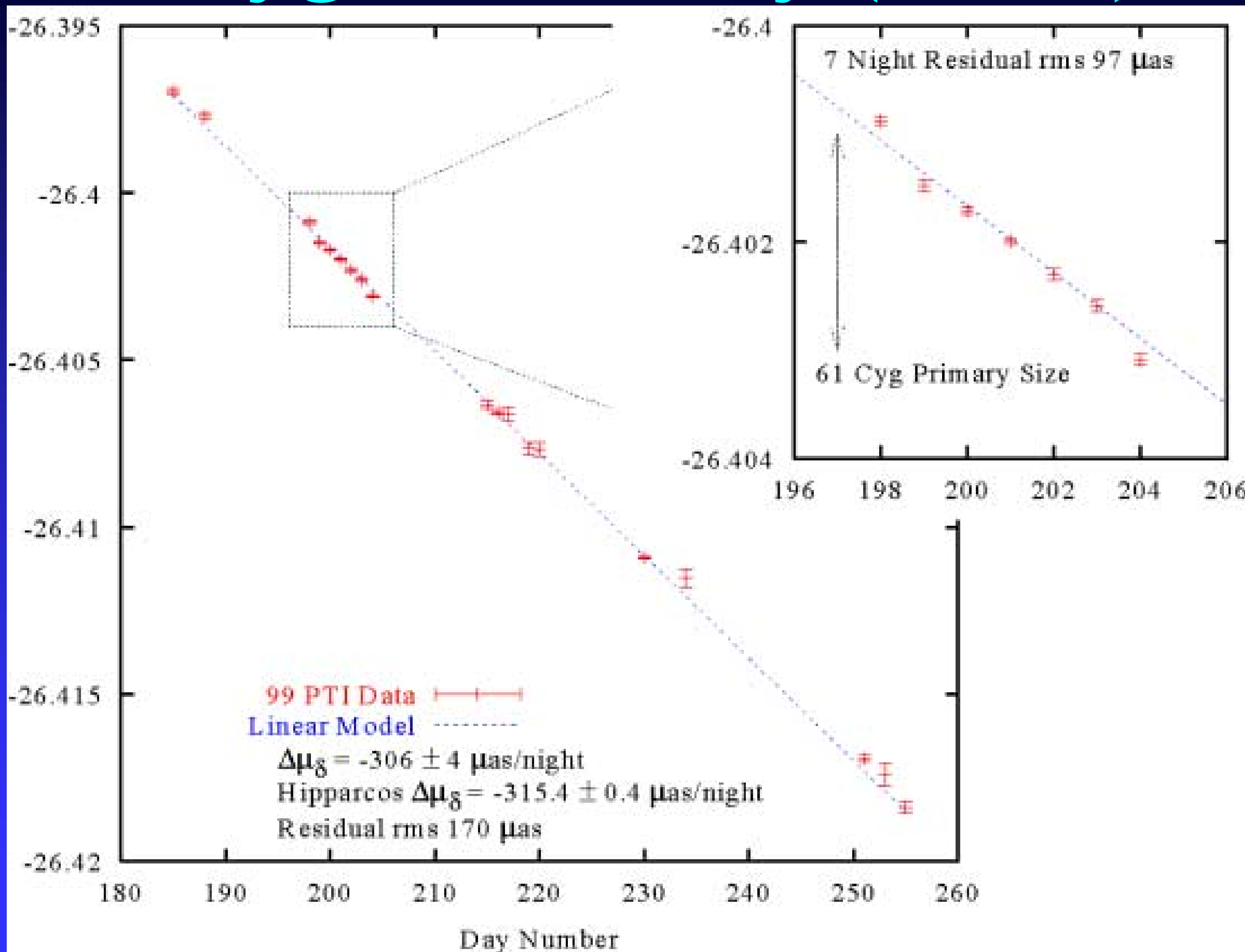


Figure by A. F. Boden & ISC

Why Phase Referencing?

- Narrow-angle astrometry requires 2 stars to be tracked (target + reference)
  - Interferometers have notoriously low sensitivity (PTI: $m_K < 5.5$)
- Need a way to use one bright star with fainter references or we're limited to visual binaries

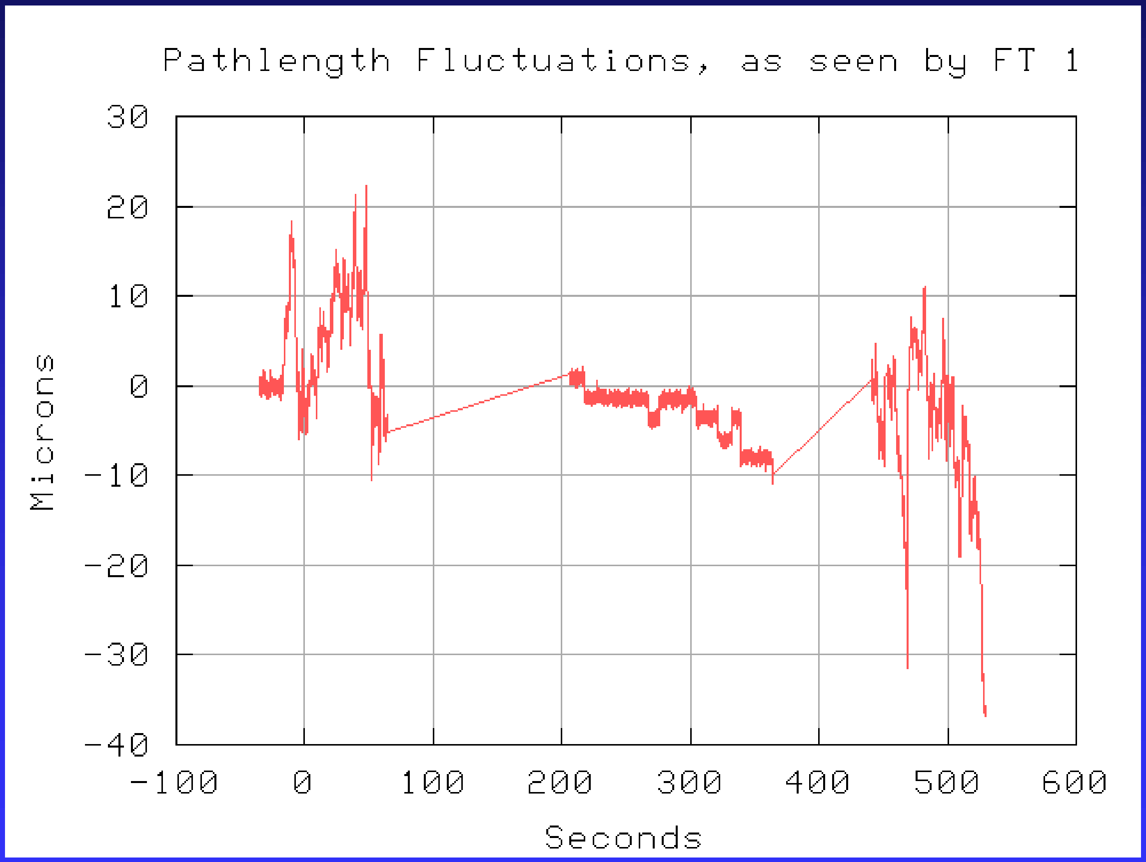
➢ Phase Referencing

What is Phase Referencing ?

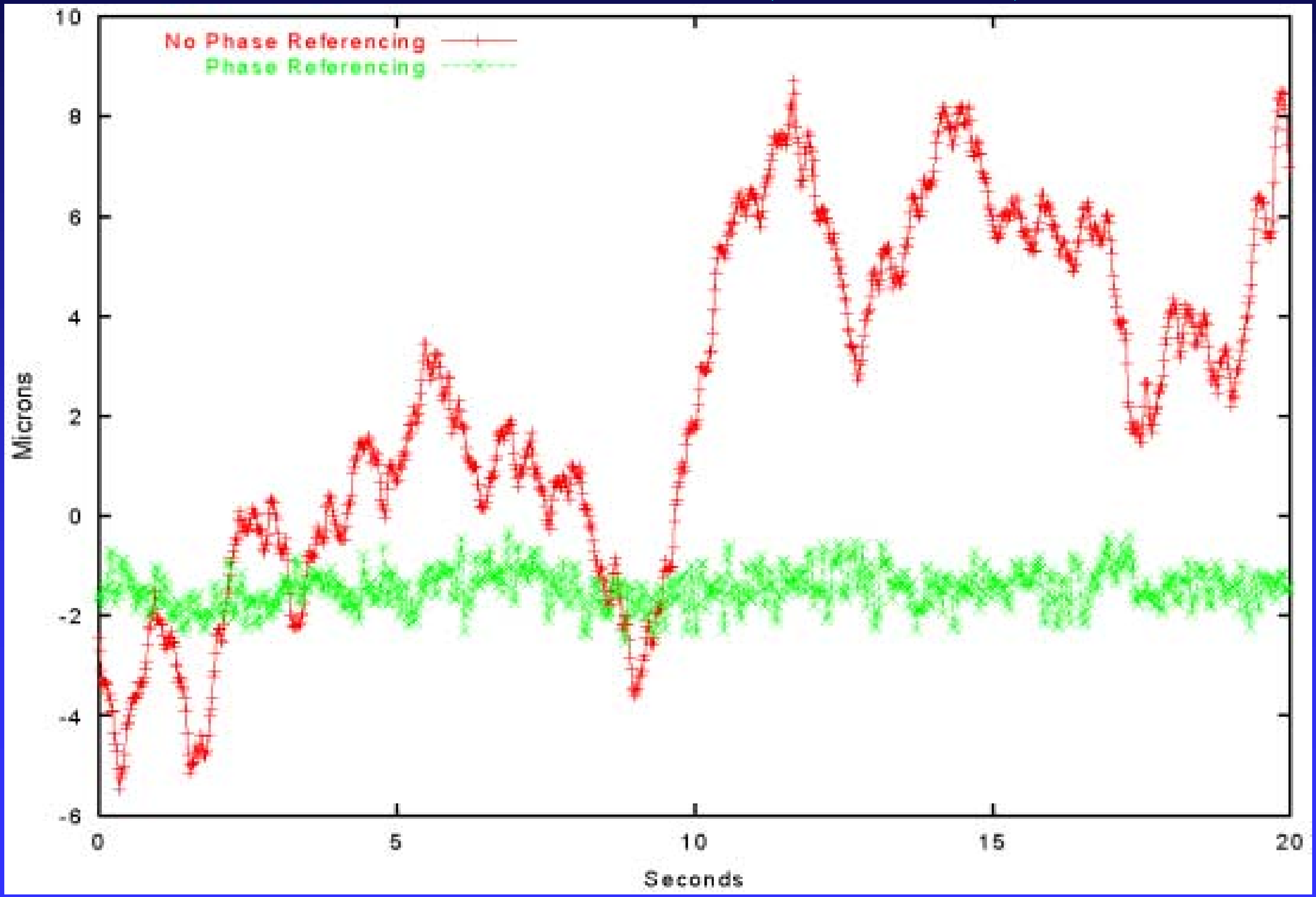
- Analogous to NGS adaptive optics on a large telescope:
  - Fringe track on a bright star within the isokinetic patch of the target star (30-50 asec)
  - Measure fringe motion induced by atmosphere
  - Correct using optical delay lines
- Allows integration times longer than would ordinarily be possible (250 ms achieved)
- Well suited for astrometry since we’re looking at nearby (and thus bright) stars by design.

Phase Referencing in Practice

- Experiment at PTI
- 2 bright stars
- One FT tracking, other just measuring fringe phase
- Data with loop open and closed

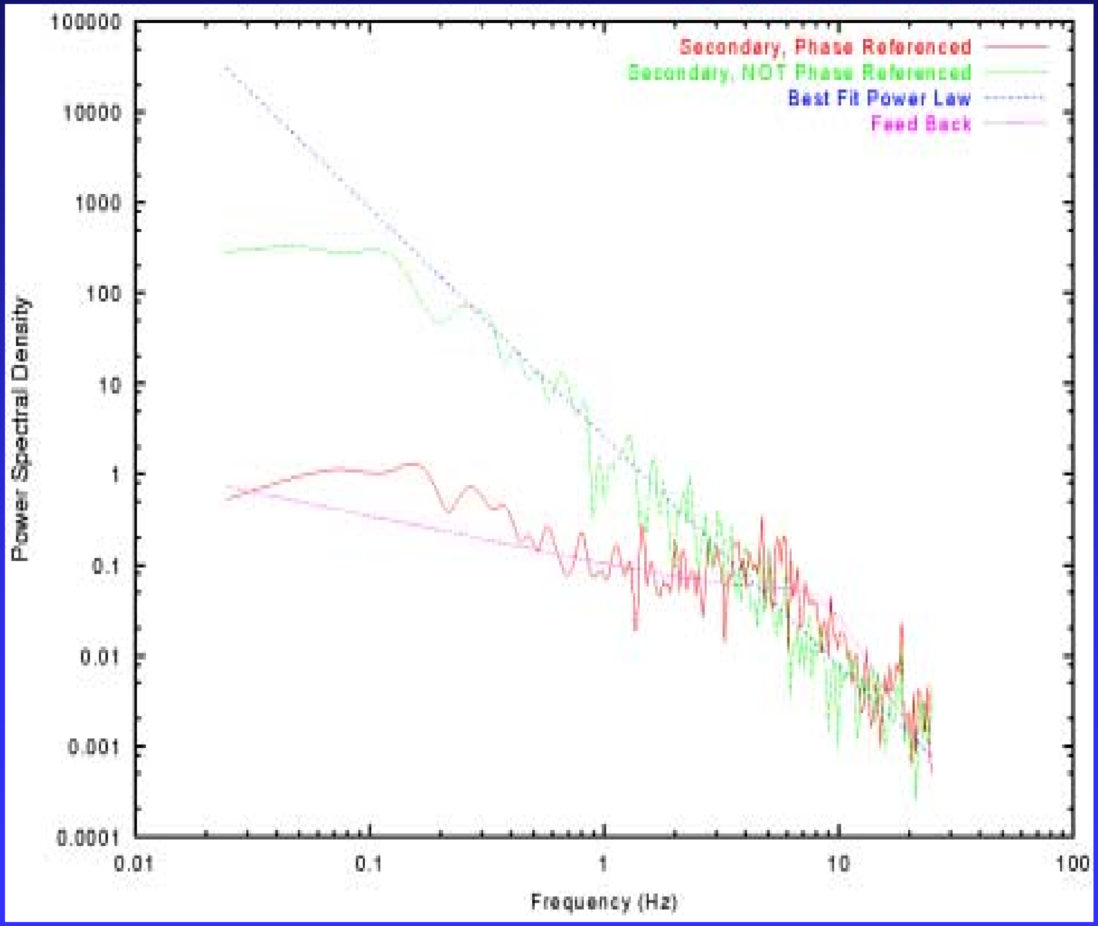


In Practice (2 of 2)



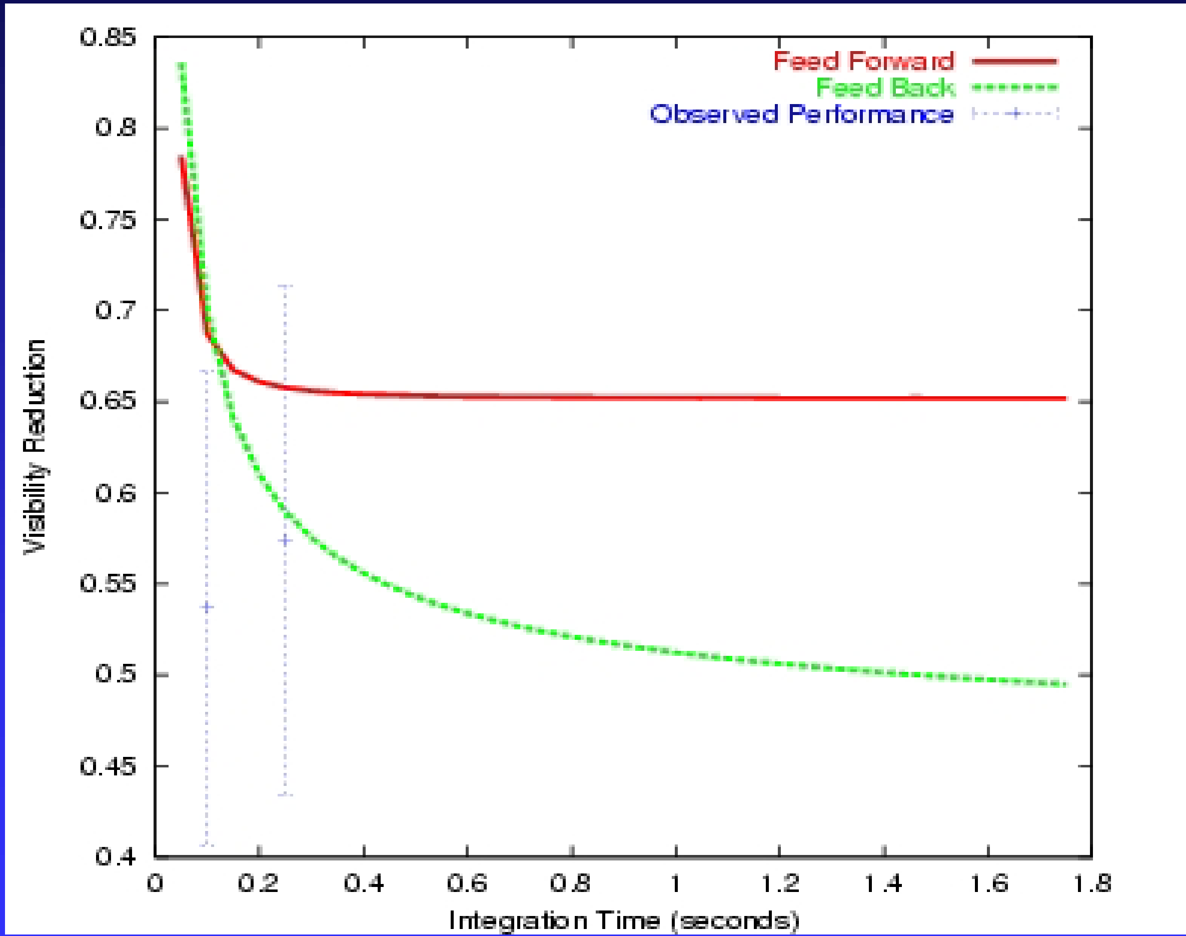
Phase Referencing Servo

- Cuts out frequencies below FT bandwidth
- Depends on details of system (processing speed)



Phase Referencing (2)

- Residual fringe motion causes visibility loss
- Effect depends on details of servo (“Feed Forward” or “Feedback”)
- Can usually expect 35-50% visibility loss



Design Considerations

- Choose site with good seeing, no high-altitude winds (South Pole).
- 2 orthogonal baselines (3-4 apertures, or rotational synthesis at Pole).
- Long baselines (200 meters).
- Choose a robust internal metrology system (multi-color) in the center of the beam.
- Consider using siderostats (easier to measure/model/control systematics).

Summary

- Narrow-angle astrometry allows 10-100 micro-arcsecond precision from the ground using modest (2-m class) telescopes.
  - Sufficient to study outer-Solar-system type planets and a good way to get masses.
- It requires significant care in instrument design, and patience from the observer (and funding agency!).